Transverse Single-Spin Asymmetry for Inclusive and Diffractive Electromagnetic Jets at Forward Rapidities in $p^{\uparrow}$+p Collisions at $\sqrt{s} = 200\ GeV$ and 510 GeV at STAR

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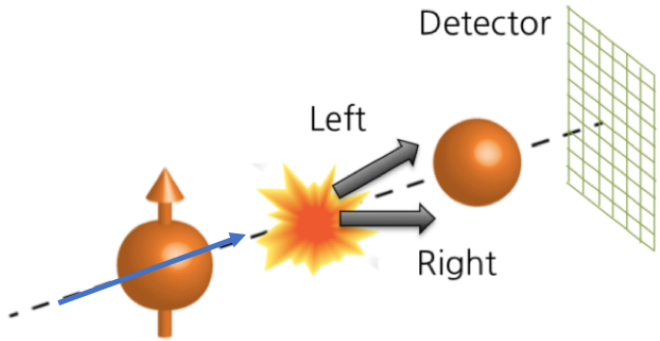
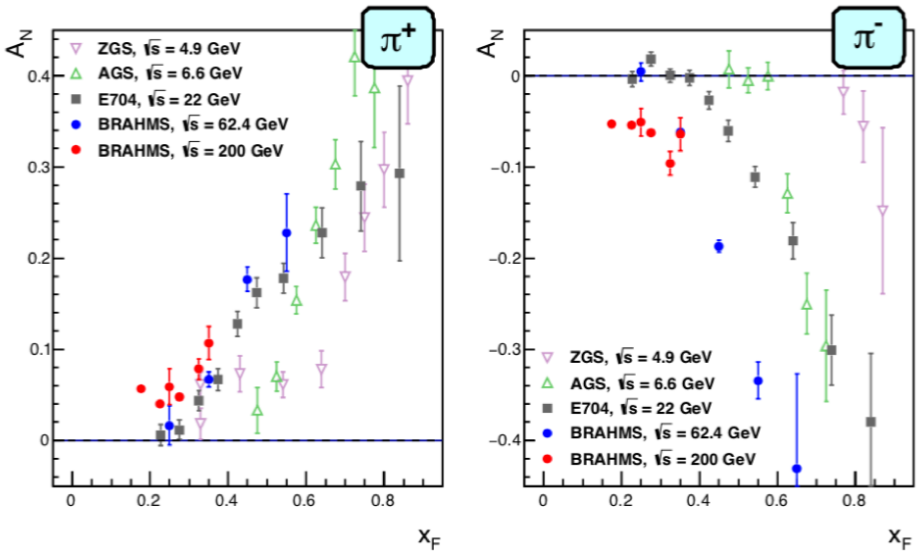
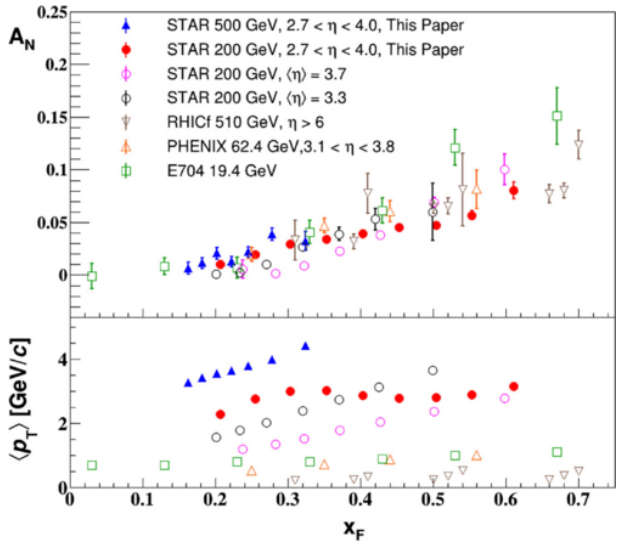
Transverse Single-Spin Asymmetry (TSSA, A_N)

- $A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$
- pQCD predicts $A_N \sim \frac{m_q \alpha_s}{\sqrt{s}} \sim 0.001$
- Unexpectedly large A_N at forward region is observed in proton-proton collisions







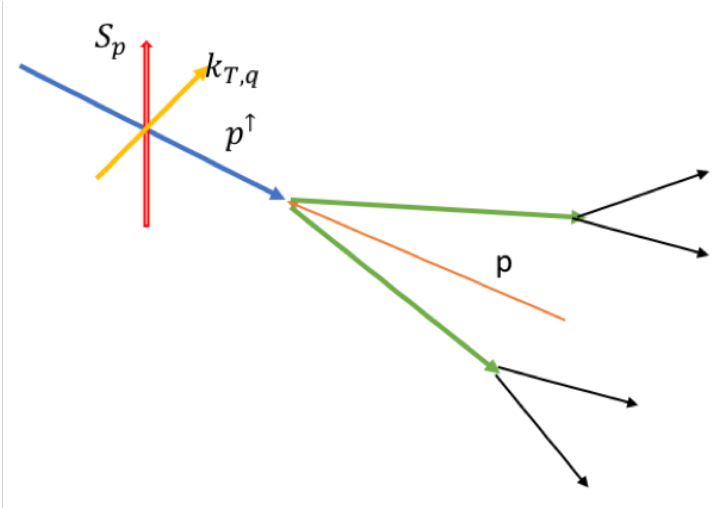
References:

- R. D. Klem et al., Phys. Rev. Lett. 36, 929 (1976)
- C. E. Allgowe et al., Phys. Rev. D 65, 092008 (2002)
- D. L. Adams et al., Phys. Lett. B264, 462 - 466 (1991)
- I. Arsene et al., Phys. Rev. Lett. 101, 0420010 (2008)
- (STAR) J. Adam *et al.*, Phys. Rev. D 103, 092009 (2021)
- D. L. Adams et al., Phys. Lett. B 261, 201(1991)
- B. I. Abelev et al., Phys. Rev. Lett. 101, 222001 (2008)
- A. Adare et al., Phys. Rev. D 90, 012006 (2014)
- E.C. Aschenauer et al., arXiv:1602.03922

Possible Mechanisms for TSSA

- **TMDs framework**:

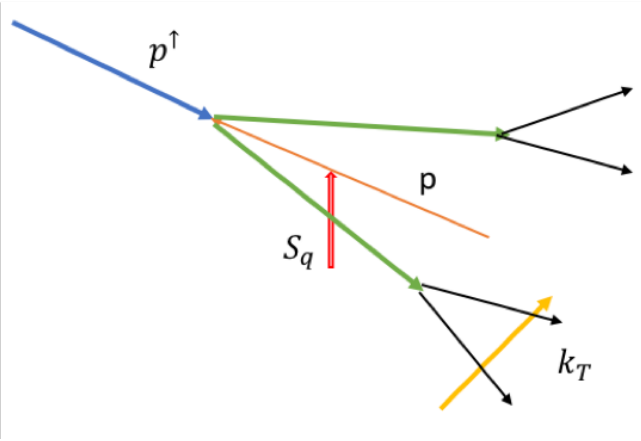
Sivers effect :correlation between initial parton k_T and proton spin



Ref: D. Sivers, Phys. Rev. D 41, 83 (1990)

Signatures: A_N for jets or direct photons, $W^{+/-}$, Z , Drell-Yan

Collins effect :correlation between fragmentation hadron k_T and its parent parton spin



Ref: J. Collins, Nucl Phys B 396 (1993) 161

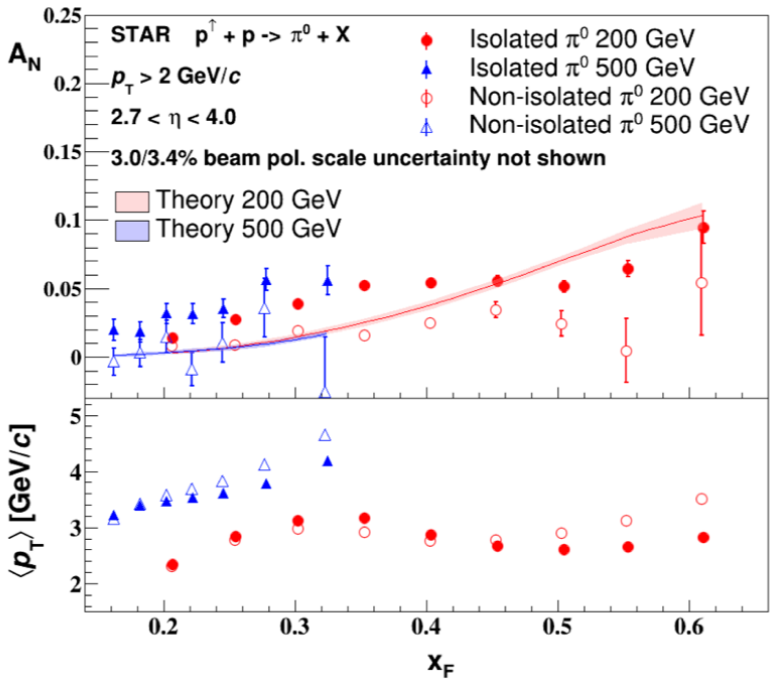
Signatures: Collins effect (Azimuthal asymmetry of hadrons in jets)

- **Twist-3**: Quark-gluon / gluon-gluon correlations and fragmentation functions.
  Ref: J.W. Qiu and G. Sterman, Phys. Rev. Lett. 67 2264 (1991)

Indication of Large TSSA from Diffractive Process

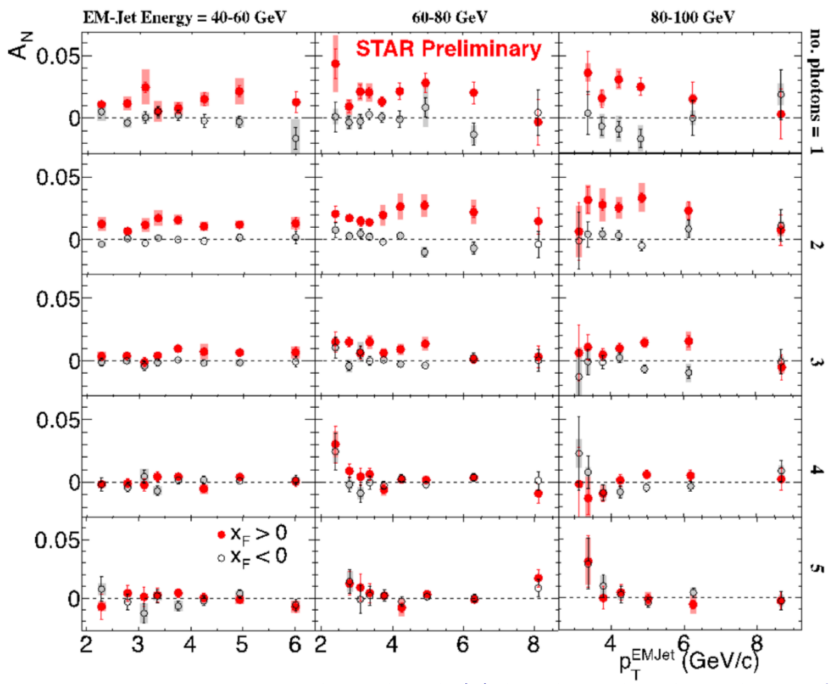
Previous analyses of A_N for forward π^0 and electromagnetic jets in $p^{\uparrow}$+p collisions at STAR indicated that there might be non-trivial contributions to the large A_N from diffractive processes.

- Inclusive π^0 A_N
  - Isolated π^0 have larger A_N



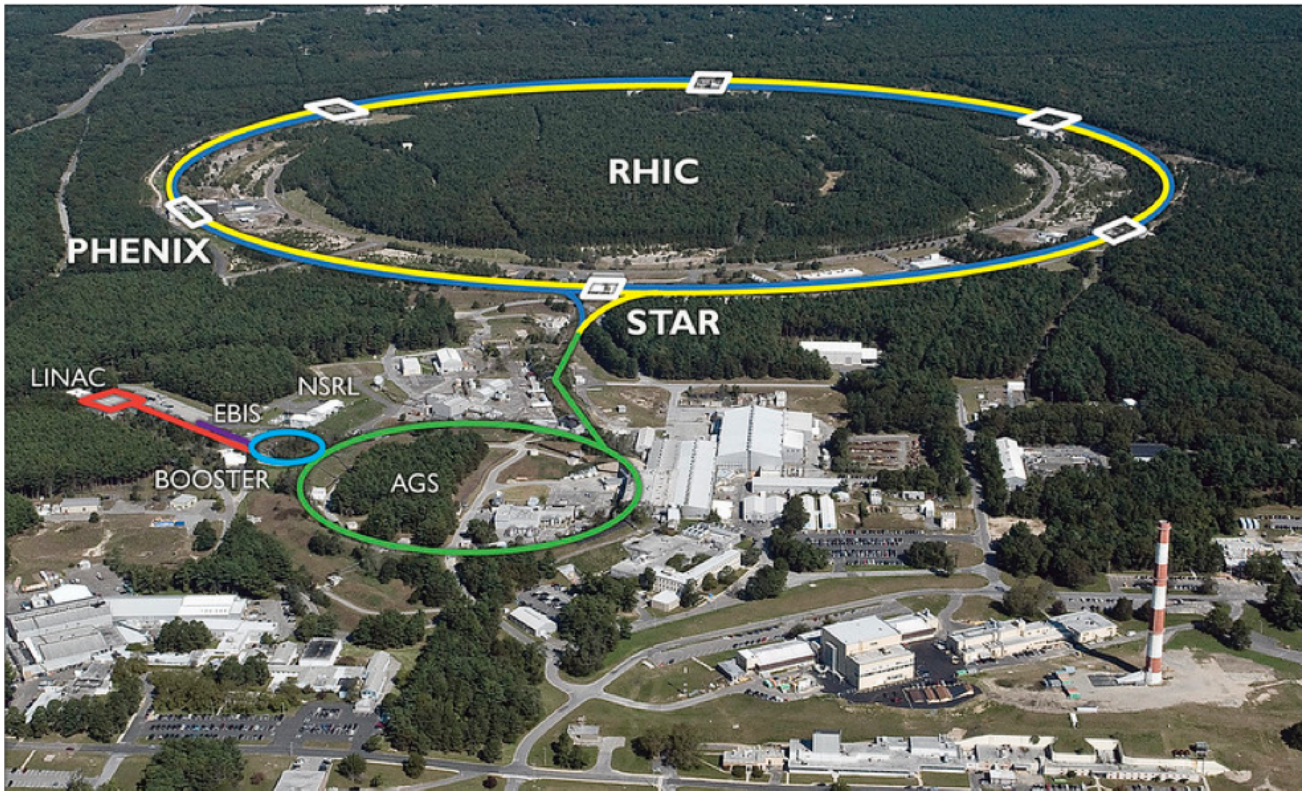
Ref: (STAR) J. Adam *et al.*, Phys. Rev. D 103, 092009 (2021)

- Inclusive EM-jet A_N
  - Low photon multiplicity jets have larger A_N



RHIC: Relativistic Heavy Ion Collider

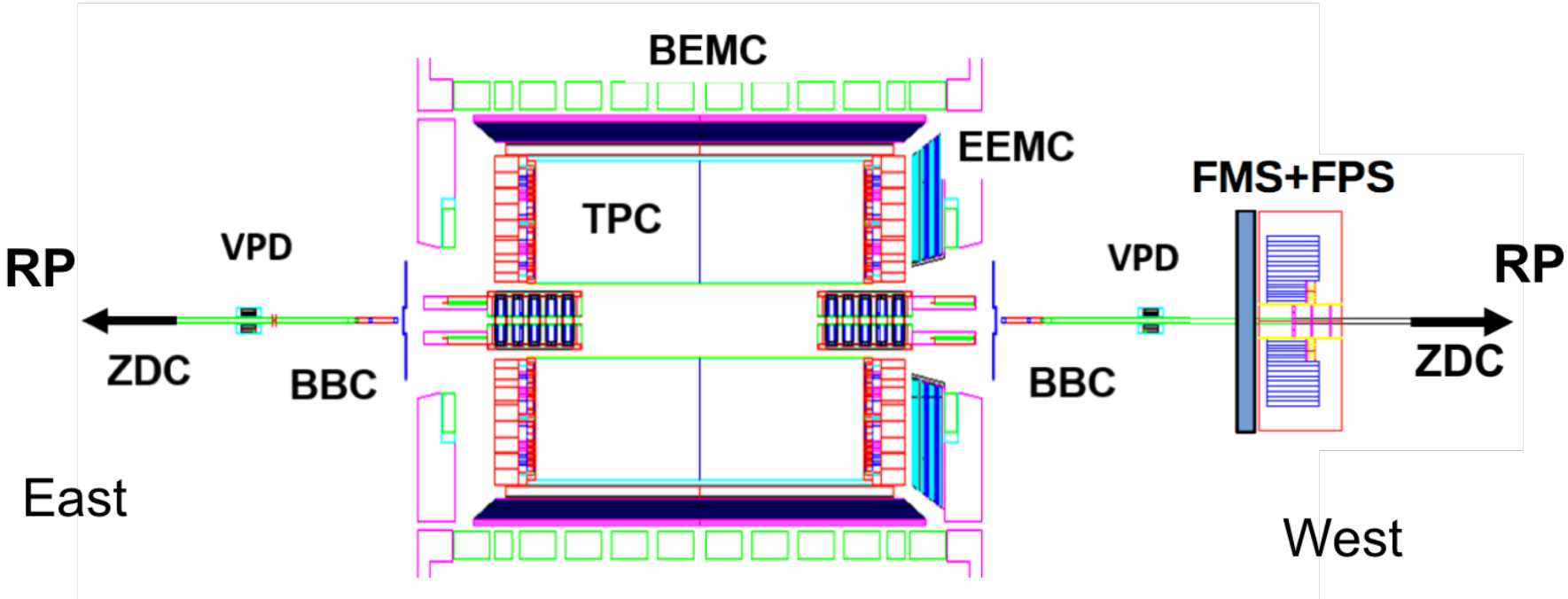
- Located at Brookhaven National Laboratory (BNL) on Long Island, NY, USA
- World's only polarized proton-proton collider
- Transverse and longitudinal polarization
- Allows polarized p-p collisions for $\sqrt{s} = 200$ - 510 GeV



STAR Experiment at RHIC

STAR sub-detectors used in the A_N analyses

- Calorimetry system: BEMC, EEMC and **FMS**
  - Forward Meson Spectrometer (FMS): $2.6 < \eta < 4.2$, $\phi \in (0, 2\pi)$
- Roman Pot (RP) allows detection of scattered protons.
- ZDC, VPD and BBC are trigger detectors.



Datasets

Year	$\sqrt{s}$ [GeV]	$\mathcal{L}[pb^{-1}]$	Polarization orientation	Polarization P (%)
2011	500	25	Transverse	48
2015	200	52	Transverse	57
2017	510	350	Transverse	55

- Previously published STAR analyses on inclusive EM-jet A_N use 2011 and 2015 data.
  - Analyses: (STAR) J. Adam *et al.*, Phys. Rev. D 103, 092009 (2021)
- Current inclusive and diffractive EM-jet A_N use 2015 data.
- Inclusive EM-jet A_N for 2017 data is in progress.

Inclusive EM-jet A_N at Forward Rapidity using FMS

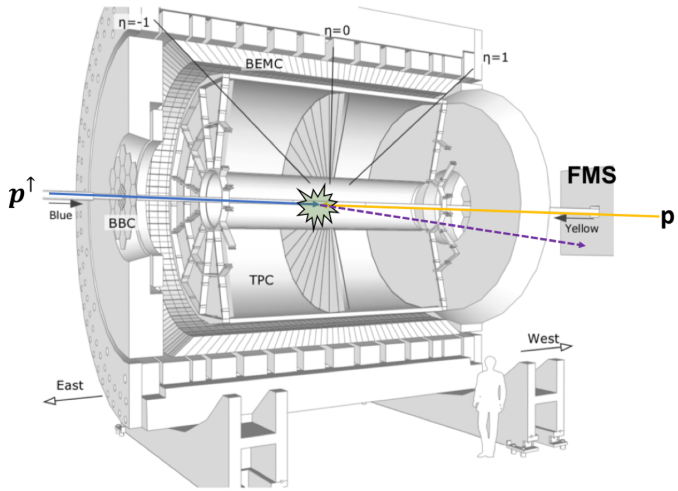
Inclusive EM-jet production: $p^{\uparrow} + p \rightarrow$ EM-jet + X

★ Motivation:
- Explore potential sources of large A_N
- Characterize EM-jet A_N as a function of EM-jet p_T, energy and photon multiplicity

★ EM-jet reconstruction
- Only reconstructed FMS photon candidates as input for FastJet
- Anti-k_T algorithm with R = 0.7
- $E_\gamma > 1$ GeV
- EM-jet $p_T > 2$ GeV/c

★ Corrections based on simulation
- PYTHIA 6.4 Perugia 2012 with GEANT based STAR detector simulation

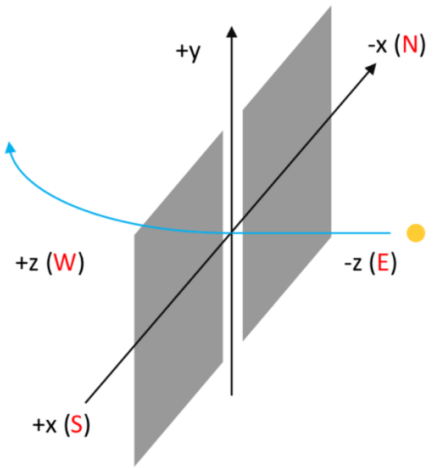
1. EM-jet p_T is corrected for Underlying Event using off-axis cone method
2. EM-jet energy is corrected to the particle level.

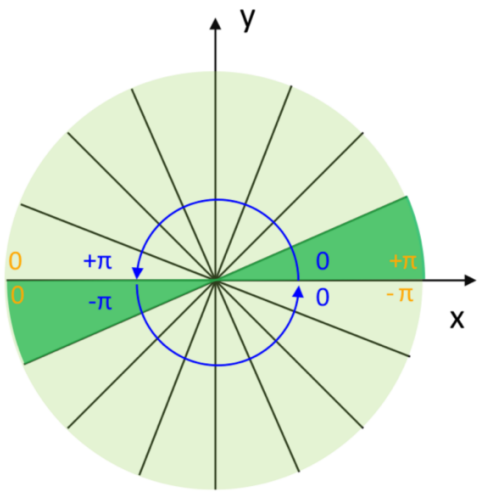


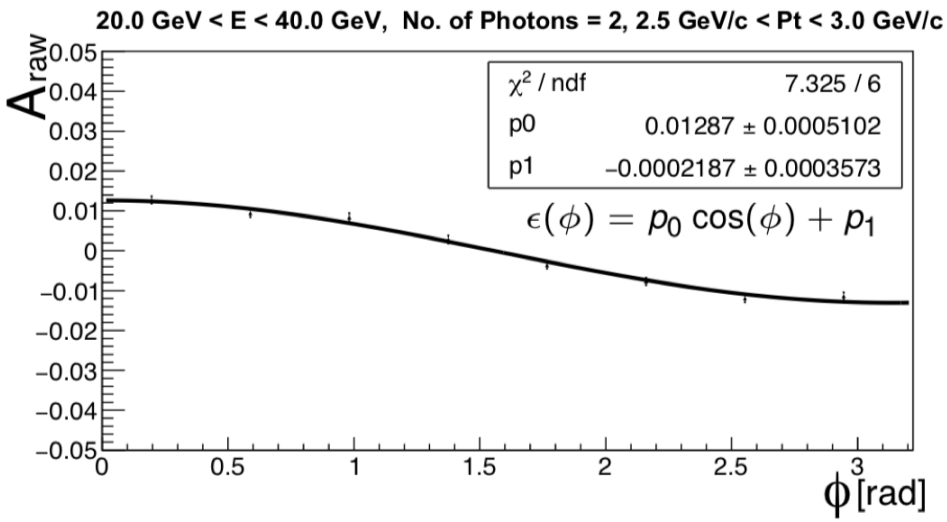
EM-jet A_N Extraction

- The cross-ratio method is used to calculate A_N.
- This method can take advantage of detector azimuthal symmetry and cancel effects on detector acceptance and beam luminosity.

$$\epsilon = PA_N cos(\phi) = \frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}$$

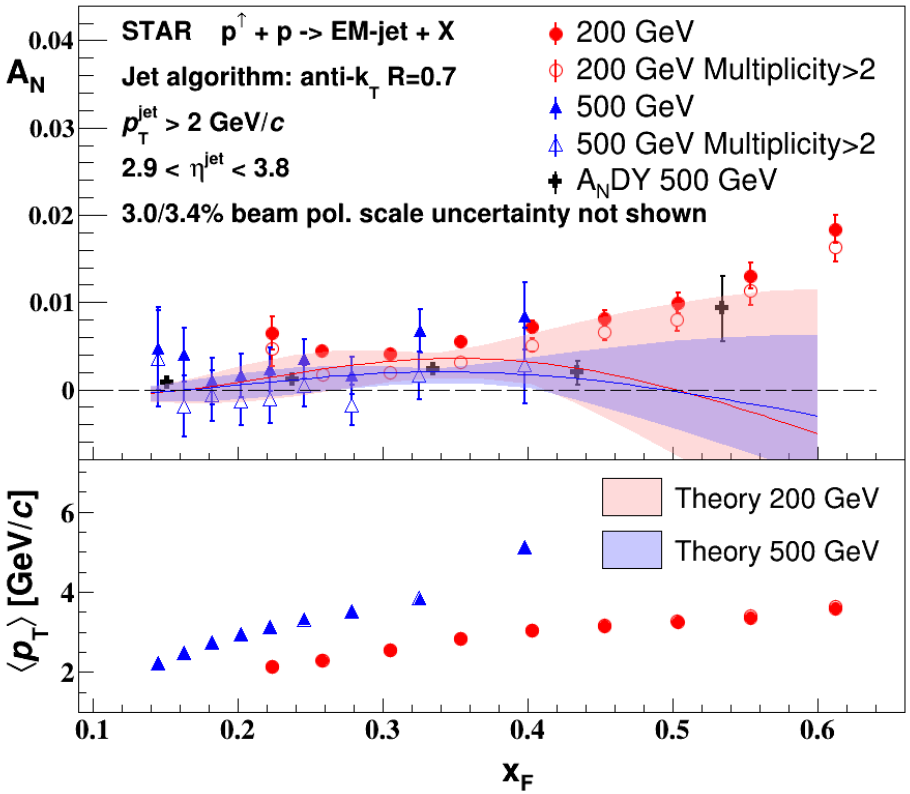






Inclusive EM-jet A_N at 200 and 500 GeV

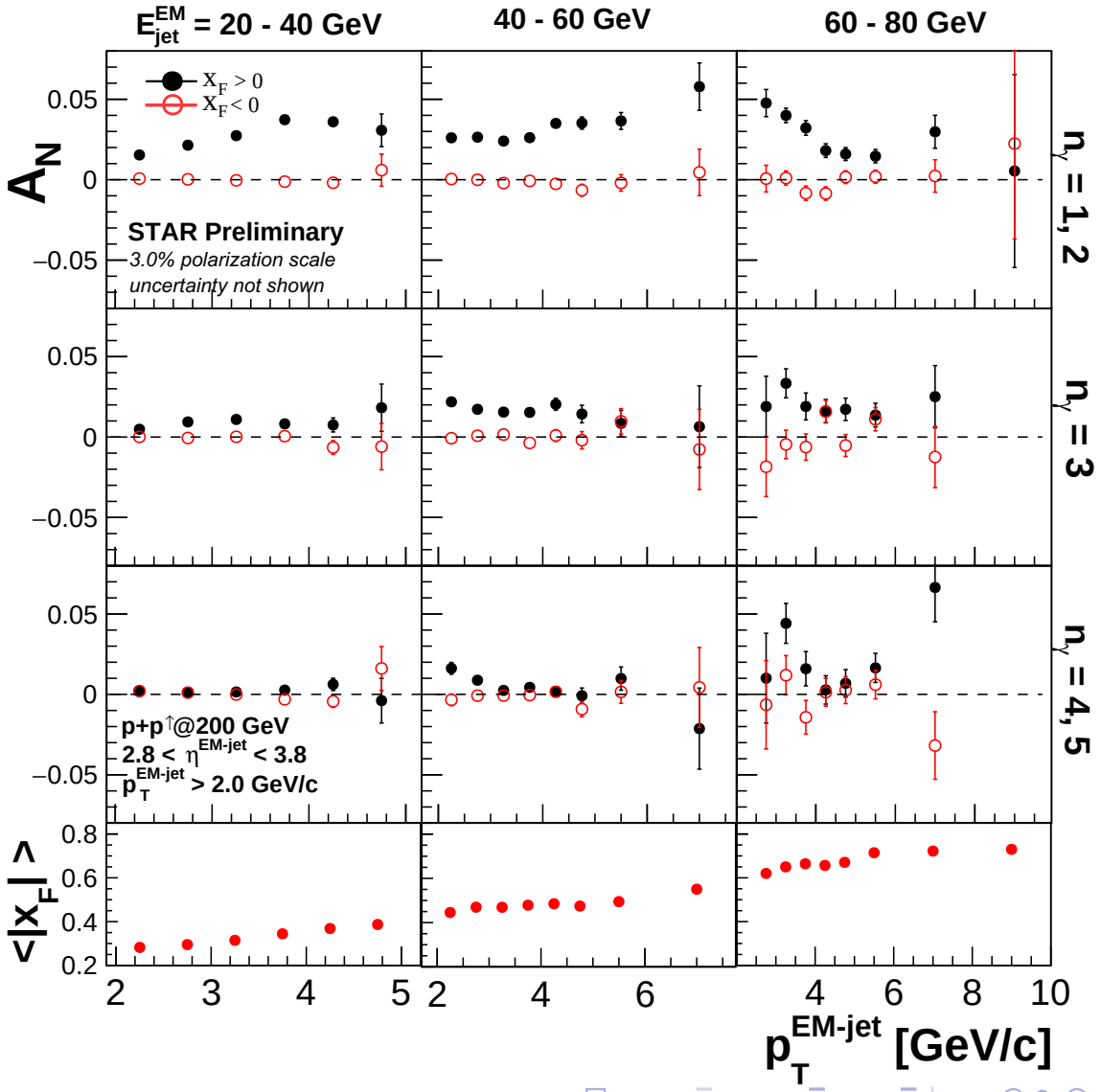
- A_N of the EM-jets increases with x_F and a week energy dependence is preferred.
- EM-jets with more than 2 photons have smaller A_N than those without this requirement.



(STAR) J. Adam *et al.*, Phys. Rev. D 103, 092009 (2021)
Theory curves: L. Gamberg, Z. Kang, A. Prokudin, Phys. Rev. Lett. 110 23 232301 (2013)

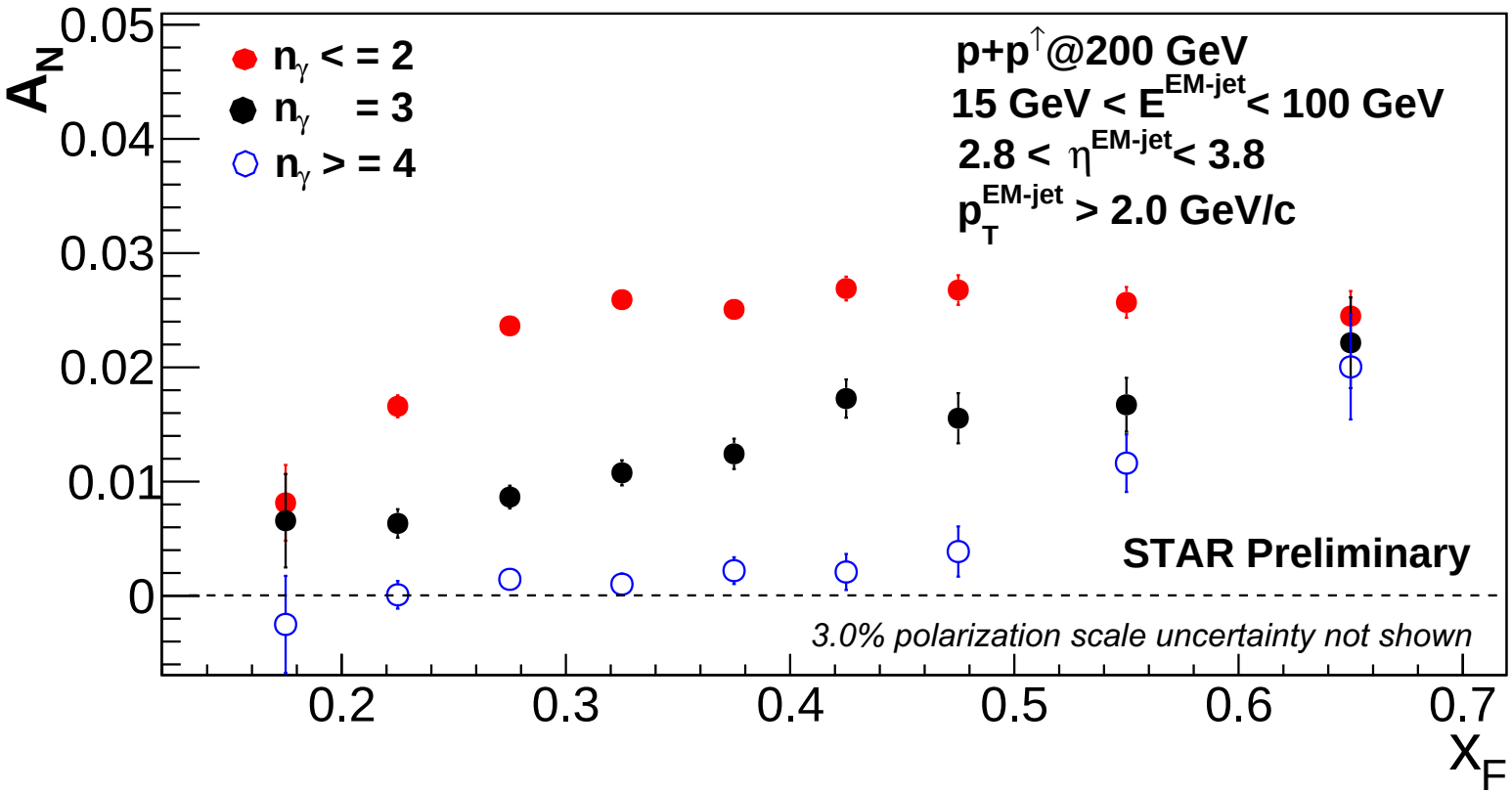
Detailed Investigations of Inclusive EM-jet A_N at Forward Rapidity at 200 GeV

- The EM-jet A_N decreases with increasing photon multiplicity (jettiness)
  - A_N is the strongest for the EM-jets consisting of 1 or 2 photons.
  - A_N is lower for EM-jets consisting of 4 or 5 photons.
- A_N at $x_F < 0$ is consistent with 0.
- The systematic uncertainties (box) mainly come from possible misidentification of the event category.



Inclusive EM-jet A_N at Forward Rapidity at 200 GeV

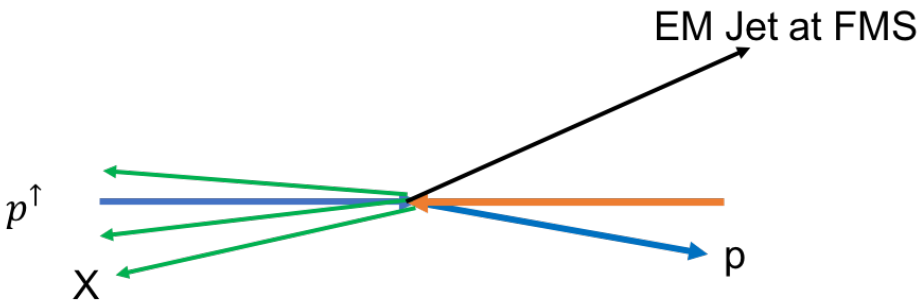
- A_N increases with the increasing x_F.
- EM-jets consisting of 1 or 2 photons have the strongest A_N.
- EM-jets with 3 photons have non-zero A_N but smaller than that of 1-photon or 2-photon EM-jets.
- EM-jets with at least 4 photons have significantly smaller A_N.



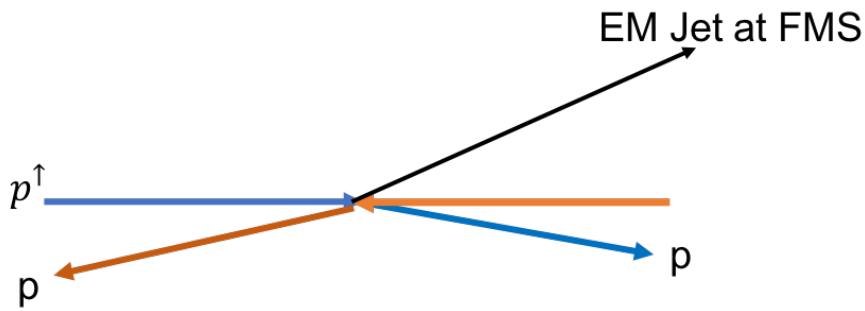
Diffractive EM-jet A_N at Forward Rapidity

- ★ **Motivation:** Measure diffractive contributions to A_N in polarized p+p collisions.
- ★ **2 possible diffractive channels:**

① Only 1 proton track on FMS side and no proton track on the away side.



② Only 1 proton track on FMS side and only 1 proton track on away side.



- ★ **Requirements:** The scattered proton must be detected by Roman Pot.
- ★ **Limitation:** They are relatively rare processes, but have been observed at STAR.

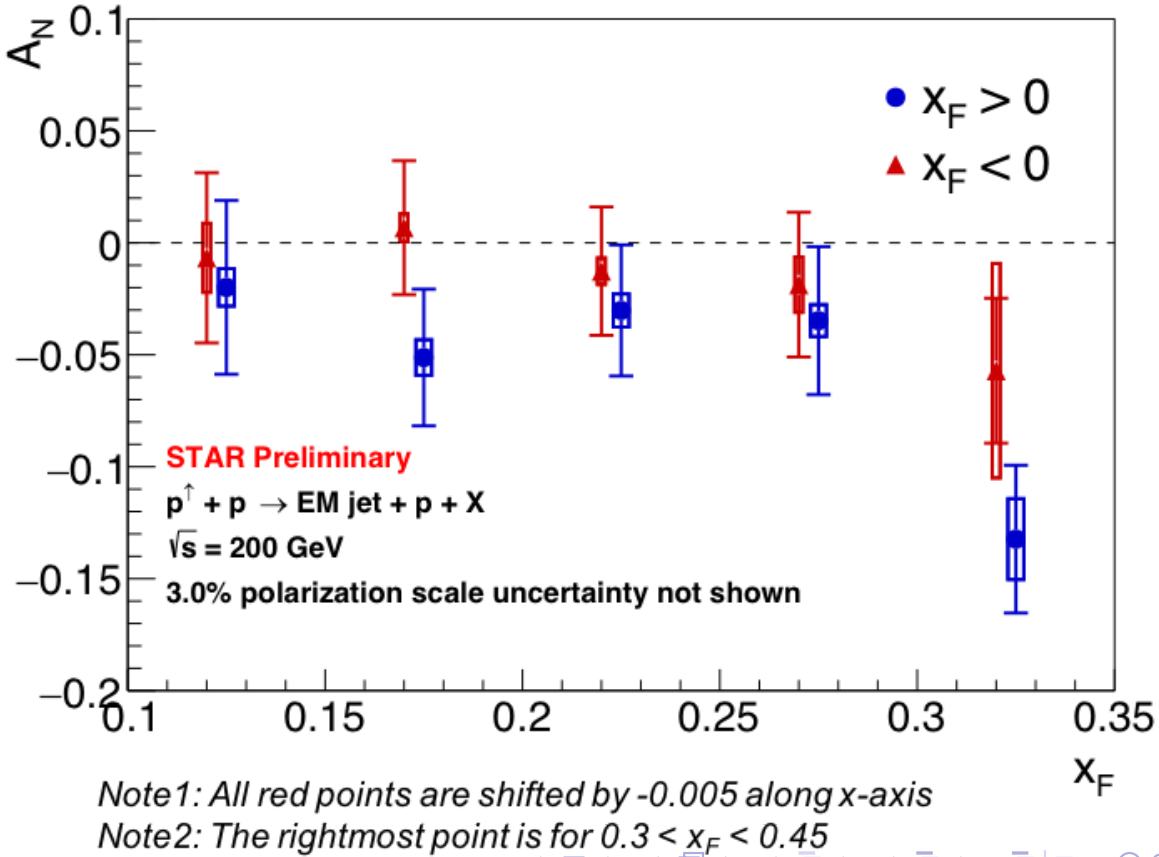
Datasets and Event Selection

- ★ Data sets: Transversely polarized $p^{\uparrow}$+p at $\sqrt{s} = 200$ GeV collected in 2015.
- ★ FMS EM-jet reconstruction
  - Only reconstructed FMS photon candidates as input for FastJet
  - Anti-k_T algorithm with R = 0.7
  - EM-jet $p_T > 1$ GeV/c
- ★ RP track selection
  - RP track is required to be reconstructed and within geometric acceptance.
  - Two acceptable scenarios for RP tracks based on the diffractive process channels:
    1. Only 1 west side RP track and 0 east side RP track
    2. Only 1 west side RP track and 1 east side RP track
- ★ BBC hit cuts to reduce accidental coincidences.
- ★ Energy sum cuts for diffractive process to reduce pile-up effect.
  - Energy sum: E(west side RP track) + E(EM-jet)
  - Apply different energy sum cut for each EM-jet energy region based on the energy sum spectrum.
- ★ EM-jet energy is corrected to particle level.

Diffractive EM-jet A_N at Forward Rapidity at 200 GeV

- The cross-ratio method is used to extract the diffractive EM-jet A_N.
- A non-zero A_N for $x_F > 0$ is observed with 3.3-sigma significance for diffractive process at forward rapidity.
- Large A_N is observed in high x_F region.

- Sign of A_N is negative. Theoretical inputs are needed to understand the different sign.
- A_N at $x_F < 0$ is consistent with 0.
- Systematic uncertainties (boxes) mainly come from cuts for reducing background events.



Note1: All red points are shifted by -0.005 along x-axis
Note2: The rightmost point is for $0.3 < x_F < 0.45$

Conclusion

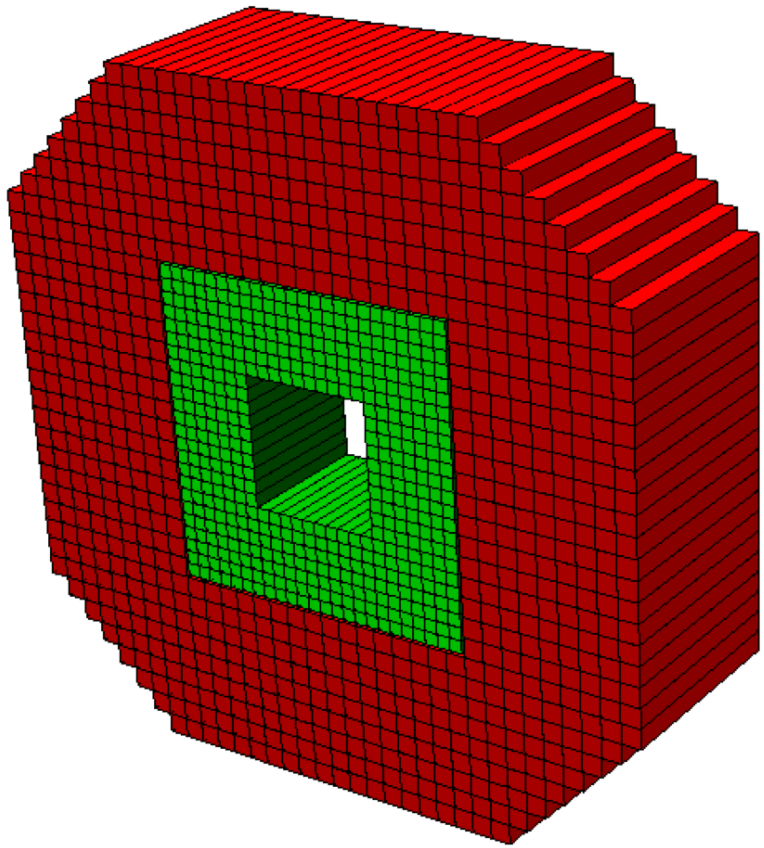
- ★ We study A_N for inclusive EM-jets with different jet substructures using the FMS at STAR in $p^{\uparrow}$+p collisions at 200 GeV.
  - EM-jet A_N decrease with increasing photon multiplicity (jettiness).
  - EM-jet A_N increase with increasing x_F.
- ★ We study A_N for diffractive EM-jets using the FMS at STAR in $p^{\uparrow}$+p collisions at 200 GeV.
  - A non-zero diffractive EM-jet A_N for $x_F > 0$ is observed. Large A_N is observed in high x_F region.
  - Sign of A_N is negative, which needs further theoretical study to understand.
- ★ Inclusive EM-jet A_N using larger $p^{\uparrow}$+p datasets taken in 2017 is underway, which will increase the statistical precision.

Back up

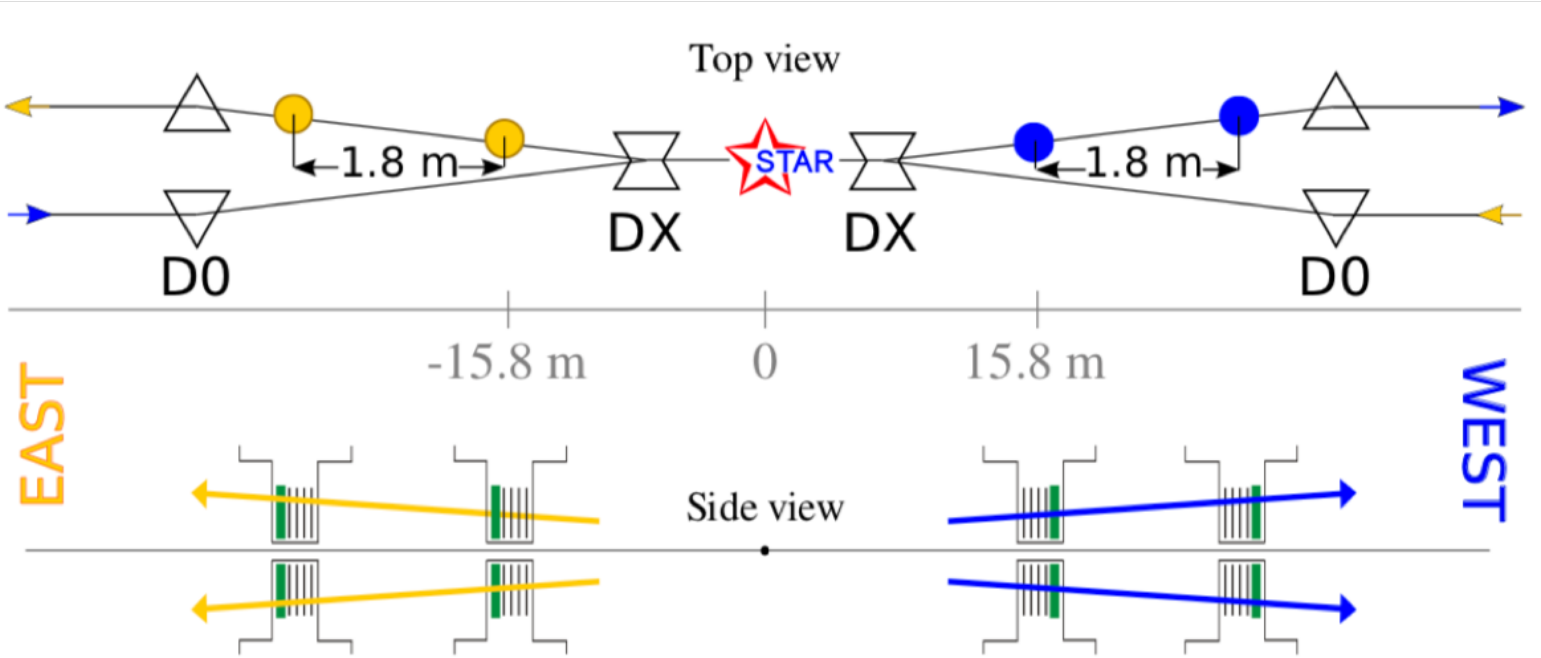
Forward Meson Spectrometer (FMS)

- FMS can detect photons, neutral pions, and eta mesons in the forward direction.
- $2.6 < \eta < 4.2$.

- FMS consists of 1264 Lead-Glass cells with photomultiplier tubes (PMT) readout connected, separated into two regions.
- Inner region (green) have smaller size cells than the outer region (red), which can provide better photon separation ability.
- All cells have $\sim$18 radiation length.



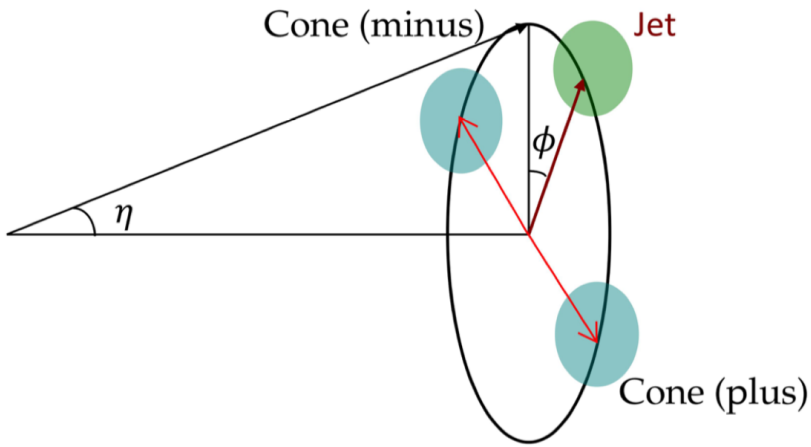
Roman Pot (RP)



- Roman Pots (RP) are vessels which house the Silicon Strip Detector planes (SSDs). They are put close to the beam pipe.
- RPs are able to detect and track slightly scattered protons close to beamline.
- 2 sets of RP (inner and outer) on each side.
- Each RP set contains a package above and below the beamline.
- 4 SSDs per package (2 x-type and 2 y-type).

Underlying Events Correction and Energy Correction

- The EM-jet p_T values are corrected for contamination from Underlying Events (UE) with off-axis cone method (right column).
- The EM-jet energy is corrected to the particle level.



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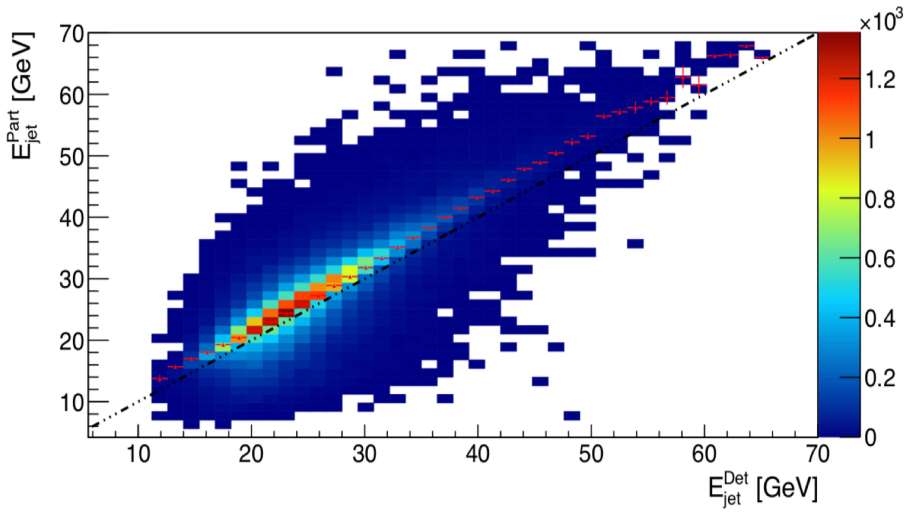


Figure: Detector EM-jet energy to particle level correction

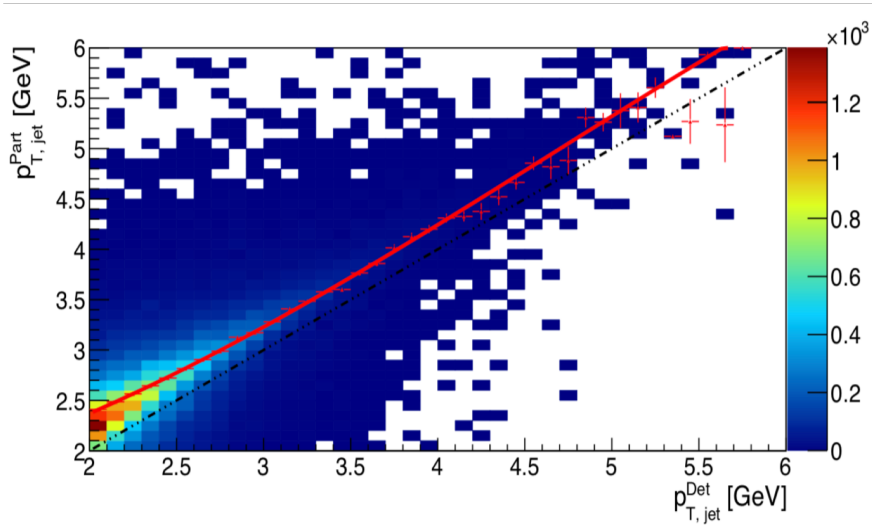
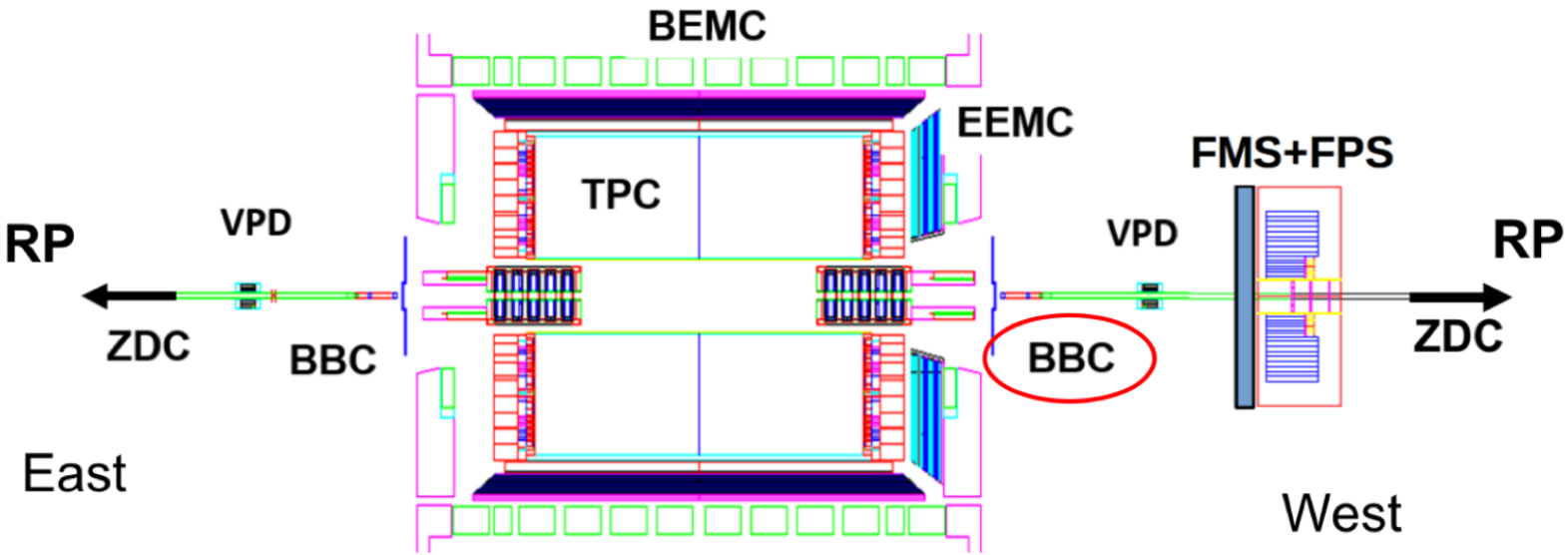


Figure: UE correction

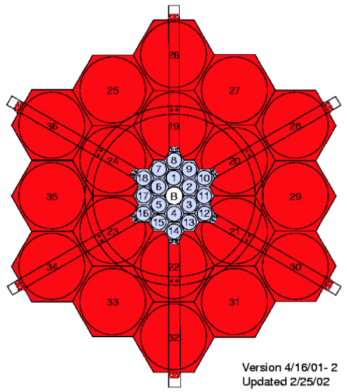
BBC hit cuts

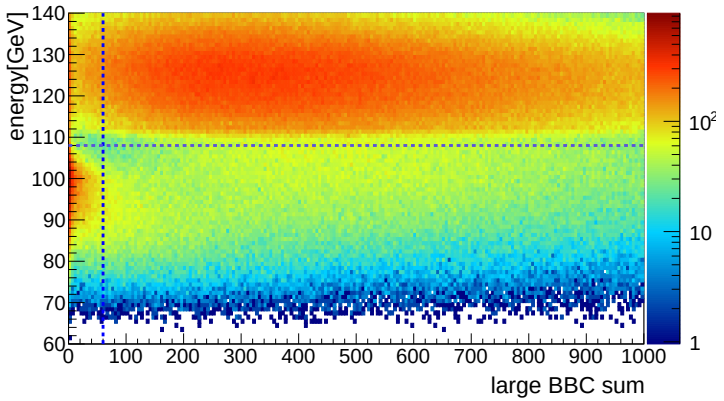
- Beam Beam Counter (BBC) can be used to triggering, monitoring luminosity and local polarimetry.
- BBC are located on both forward and backward side.
  - BBC: $2.1 < |\eta| < 5$.
- Benefits for cuts on BBC hits:
  - Reduce accidental coincidence events with a second interaction in the same bunch crossing.
  - Get rid of high luminosity events which may cause pile-up effect.
- The cut on forward BBC hits can increase fraction of signal significantly.

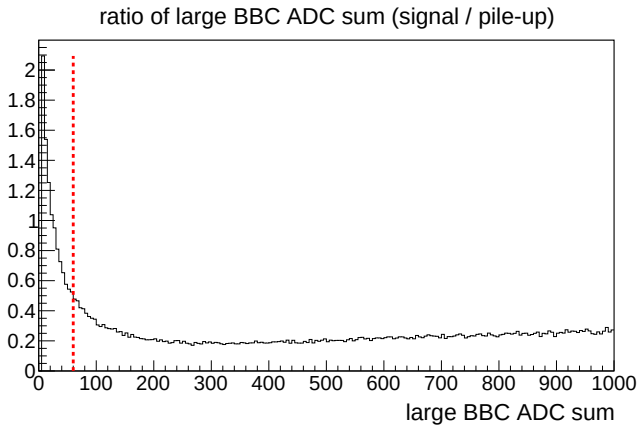


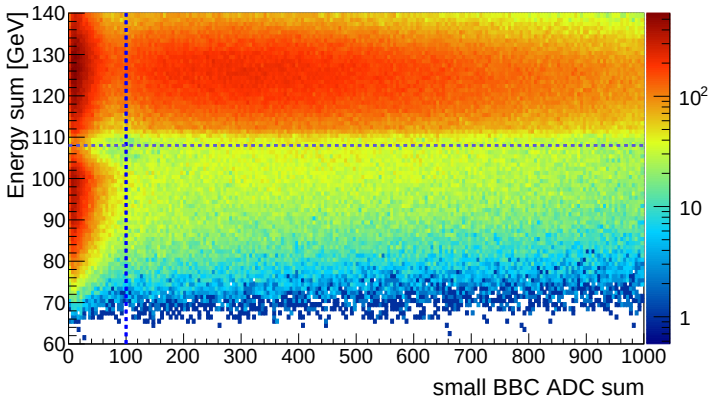
Details on BBC cuts for diffractive EM-jet A_N analysis

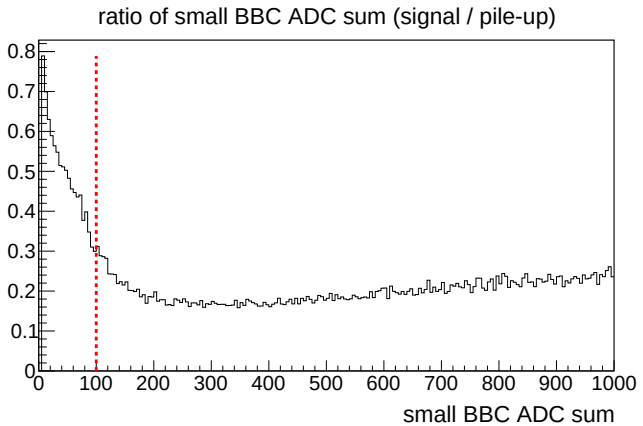
- Based on the sum energy ($E_{EM-jet} + E_{RPtrack}$) vs BBC ADC sum.
- Horizontal line ($E = 108$ GeV) splits signal and background region.
- Optimize the fraction of signal and background.











Energy sum cut

- Calculate energy sum: E(west side RP track) + E(FMS EM-jet) for each event.
- Apply energy sum cut based on the separation of diffractive process peak and pile-up peak. (Left plot as example)
- Pile-up peak mainly come from the events with RP track energy around 100 GeV (pile-up events).